Absolute Optical Metrology: Nanometers to Kilometers

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Abstract
We provide and overview of the developments in the field of high-accuracy absolute optical metrology with emphasis on space-based applications. Specific work on the Modulation Sideband Technology for Absolute Ranging (MSTAR) sensor is described along with novel applications of the sensor.

Optical distance metrology is used in a wide variety of applications: from monitoring growth of angstrom-thick epitaxial layers to pathlength stabilization between spacecraft separated by kilometers.

A number of interferometric instruments exist, both in the lab and in the field, that can readily measure nanometer-level displacements (ref), but absolute distance remains unknown, because of the inherent half-wavelength (~0.5 μm for a near-IR laser) ambiguity range. In some applications knowledge of only the relative displacement is enough, but in others it is desirable to know the absolute distance with micron or sub-micron accuracy.

Space-based applications of precision distance metrology include figure sensing in optical telescopes and radio-frequency antennas, optical pathlength control in stellar interferometers, and precision sensing and formation control of distributed spacecraft instruments and missions. For example, NASA's Space Interferometry Mission (SIM), Terrestrial Planet Finder (TPF) and ESA's Darwin mission all require very precise determination of optical pathlengths within the system. Several large optical telescope designs, currently in the proposal stages, require a sensor for both figure sensing and station keeping of the free-flying telescope elements. For space-based applications, a versatile metrology gauge must be able to operate from a few centimeters to a kilometer.

To determine the target distance with high accuracy, the ambiguity range of the fine interferometric stage must be resolved with an additional coarse gauge(s). The range accuracy of the coarse stage must be better than the ambiguity range of the fine stage; resolving a half-wavelength ambiguity range of 0.5 μm requires a 1μ absolute range accuracy of ~0.1 μm (peak-valley error ~0.5 μm). A number of methods exist for unambiguous determination of target distance.

The most common method for range determination is to measure a pulse time-of-flight. This method is fundamentally limited in resolution because range resolution of 0.25 μm implies 1.6 femtoseconds time resolution[1].

An alternative method is to impose a sinusoidal high frequency modulation on the optical carrier and measure the round trip phase of the modulation[2]. This method affords higher accuracy than the time-of-flight and performance has been demonstrated in the tens of microns range. However, the limitation of this method is that it requires both generation and direct detection of high-frequency (tens or hundreds of GHz) modulation of an optical carrier. This in turn requires operation with high returned optical power levels: a condition incompatible with long range space-based applications and practical limitations of many ground-based applications.

Two-color interferometry, in which measurements are made at different laser wavelengths. has long been a method of choice for extending the ambiguity range of optical interferometers[3,4]. Differencing these measurements is equivalent to having a laser interferometer with a much longer synthetic wavelength. High accuracy over long distances requires generation of two wavelengths with large *and* very stable frequency difference between them. Semiconductor lasers can be used to generate wavelengths with large frequency difference, but do not have the needed frequency stability to operate over practical target ranges[5,6].

Modulation Sideband Technology for Absolute Ranging (MSTAR) sensor developed at the Jet Propulsion Laboratory is a combination of two-color interferometer and carrier modulation techniques[7]. It overcomes the limitations of the existing techniques and delivers a coarse gauge accuracy of 0.13 μm sufficient to resolve the optical half-wavelength ambiguity of its underlying sensors. In the MSTAR sensor, shown in Fig. 1, the two wavelengths at which the differential

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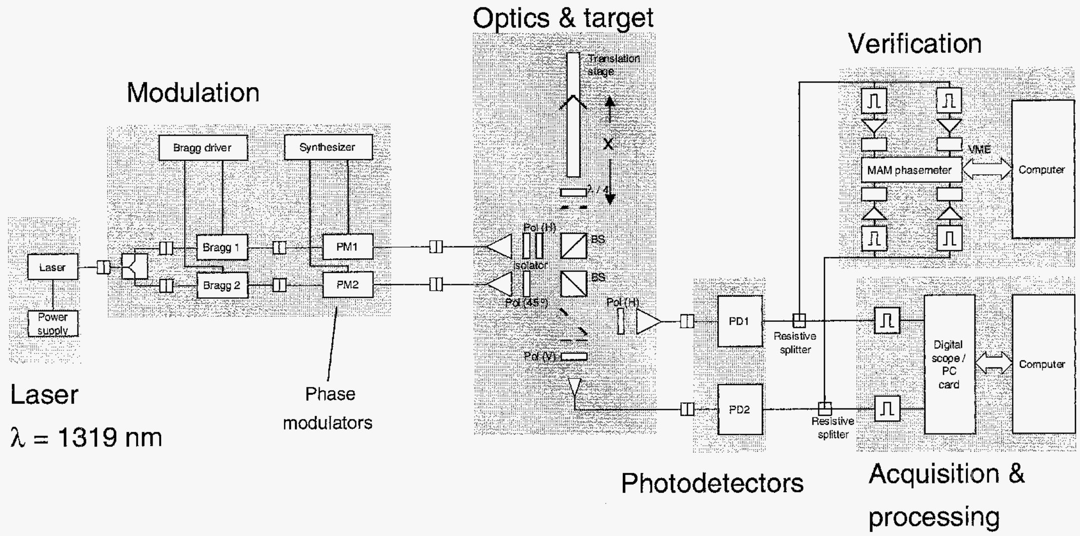

Figure 1. Schematic of the MSTAR sensor and verification setup

interferometric measurements are performed are obtained from the spectral sidebands produced by the RF phase modulation of a single carrier. In such an arrangement the stability of the frequency difference between the two wavelengths is directly tied to the RF generator and is insensitive to the frequency fluctuations of a single common-mode laser.

The performance of the MSTAR sensor was validated by comparing its coarse stage measurements to the "truth" sensor consisting of a zero-point white light interferometer and a fringe counting laser interferometer. The results are shown in Fig. 2. The coarse stage accuracy of 0.13 μm allows us to resolve the optical wavelength interferometer ambiguity and therefore extend the overall sensor accuracy to

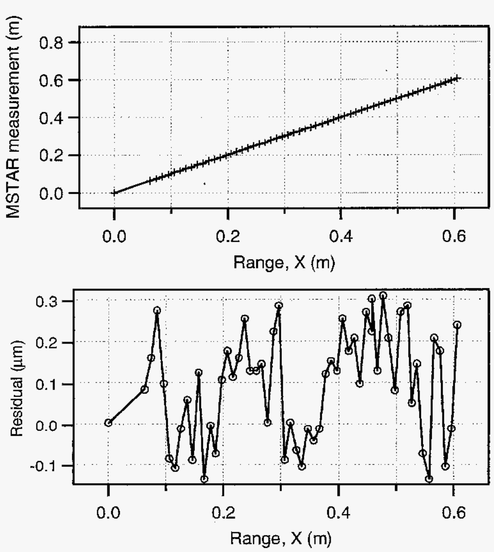

Figure 2. a) MSTAR sensor readings vs. the truth sensor, b) deviation between MSTAR and the truth sensor.

nanometer regime. The extension to nanometer accuracy requires stabilization of the optical wavelength.

Design considerations for practical applications will be discussed and the extension of the technique to 3-D position determination of multiple targets

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References

1. O. Bock, "Relative positioning precision of the wide-angle airborne laser ranging system," *J. Opt. A*, vol. 1, pp. 77-82, 1999.
2. I. Fujima, S. Iwasaki, and K. Seta, "High-resolution distance meter using optical intensity modulation at 28 GHz," *Meas. Sci. Technol.*, vol. 9, pp. 1049-1052, 1998.
3. R. Dandliker, R. Tharlman, and D. Prongue, "Two-wavelength laser interferometry using super-heterodyne detection," *Opt. Lett.*, vol. 13, pp. 339-343, 1988.
4. P. De Groot, "Three-color laser-diode interferometer," *Applied Optics 30*, pp. 3612-16, 1991.
5. C. C. Williams and H. K. Wickramasinghe, "Absolute optical ranging with 200-nm resolution," *Optics Letters 14*, pp. 542-4, 1989.
6. J. A. Stone, A. Stejskal, and L. Howard, "Diode lasers in length metrology: application to absolute distance interferometry," *CalLab*, 1999.
7. O. P. Lay, S. Dubovitsky, R. D. Peters, J. P. Burger, S. W. Ahn, W. H. Steier, H. R. Fetterman, and Y. Chang, "MSTAR: a submicrometer absolute metrology system," *Optics Letters 28*, pp. 890-2, 2003.